



Magnetic Analysis of LARP TQ Mirror Models

V.V. Kashikhin, A.V. Zlobin

Introduction

Magnetic mirror models have been used for the shell-type dipole magnets within the Fermilab HFM program [1]. They have proven to be a useful tool for studying the individual coil mechanical, thermal and quench performance under realistic conditions that greatly accelerates the magnet fabrication and test turn-around [2]. Implementation of the mirror configuration for a quadrupole magnet may provide even greater benefits because of twice-larger number of coils with respect to a dipole magnet.

We propose to apply the magnetic mirror concept for the LARP TQ magnets. In order to understand the impact of replacing the coils with the mirror blocks, a magnetic analysis was performed for several possible cases.

Collared Mirror Design

The simplest way to implement the magnetic mirror concept for the TQC magnet series is to replace three out of four coils with iron blocks inside of the collar structure. Such design would retain the magnet assembly concept and require a minimum number of additional parts. The 2D finite-element model, shown in Fig. 1, was created and analyzed by Comsol Multiphysics code. The magnetic properties of the mirror block were represented by the same B-H curve as for the iron yoke.

It is possible to see that even at high current, the magnetic field distribution around the coil is close to that of the original design [3], which ensures a similar distribution of Lorentz forces. However, the magnetic flux density exceeds 6.5 T in the mirror block, impeding its ability to conduct the magnetic flux that affects the peak field level.

Fig. 2 presents the load lines of the original (4-coil) and collared mirror designs along with the critical currents for different reference critical current densities and operating temperatures. One can see that the peak quench field in the collared mirror design is by ~0.35 T lower than that in the original design, while the quench current is by ~1 kA higher that creates a potential problem of exceeding the current capacity of the 15 kA top plate currently used for TQ magnet testing. In addition, the Lorentz force level is considerably lower in the collared mirror design, as shown in Fig. 3. While the vertical force reaches ~65 % of the original value, the azimuthal force is lower by almost a factor of two even with the corresponding correction for higher quench current in the collared mirror design.

Due to these reasons, the collared mirror design is not a good choice for reproducing the operating conditions of the original TQ magnet.

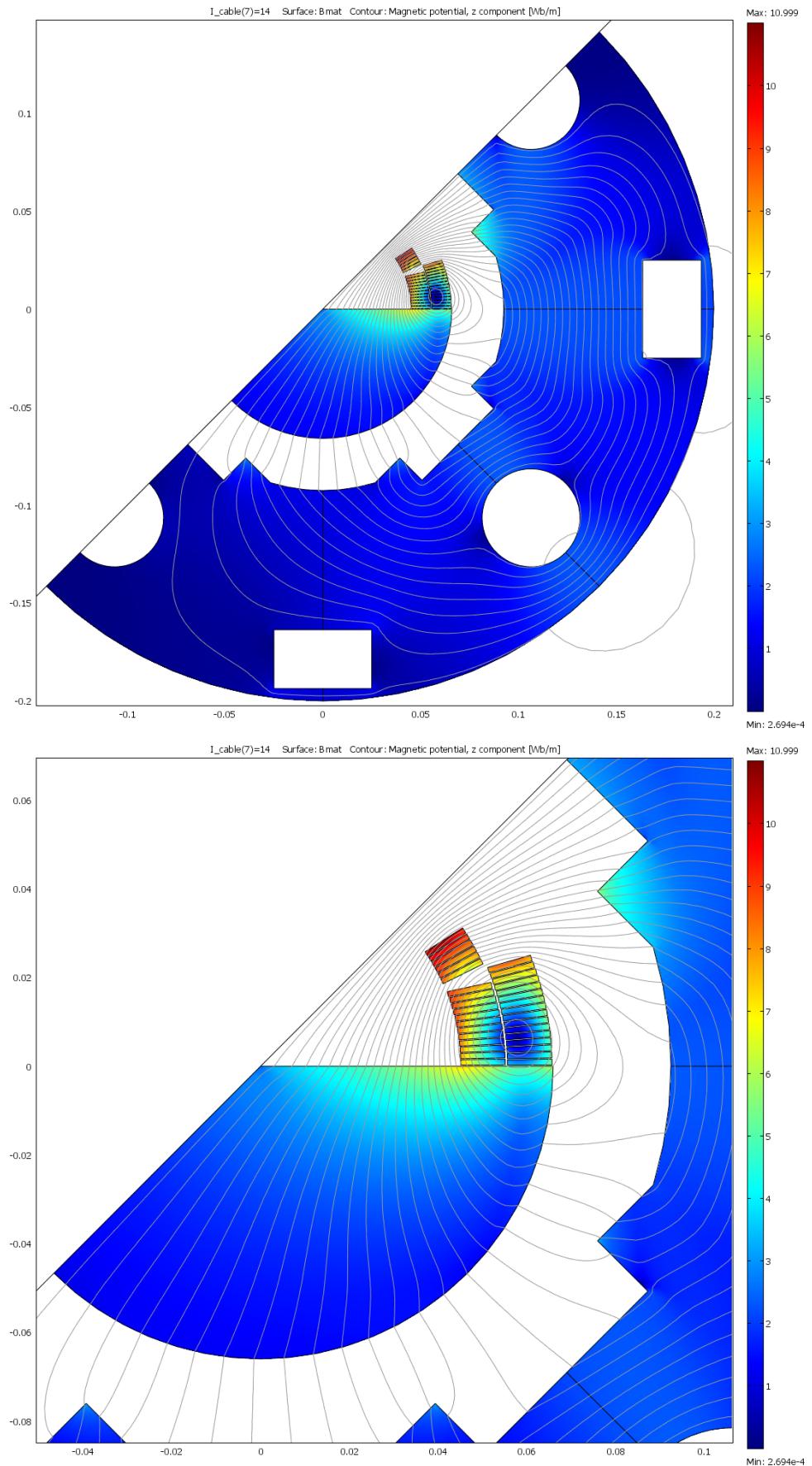


Figure 1. Magnetic field in the collared mirror design at 14 kA.

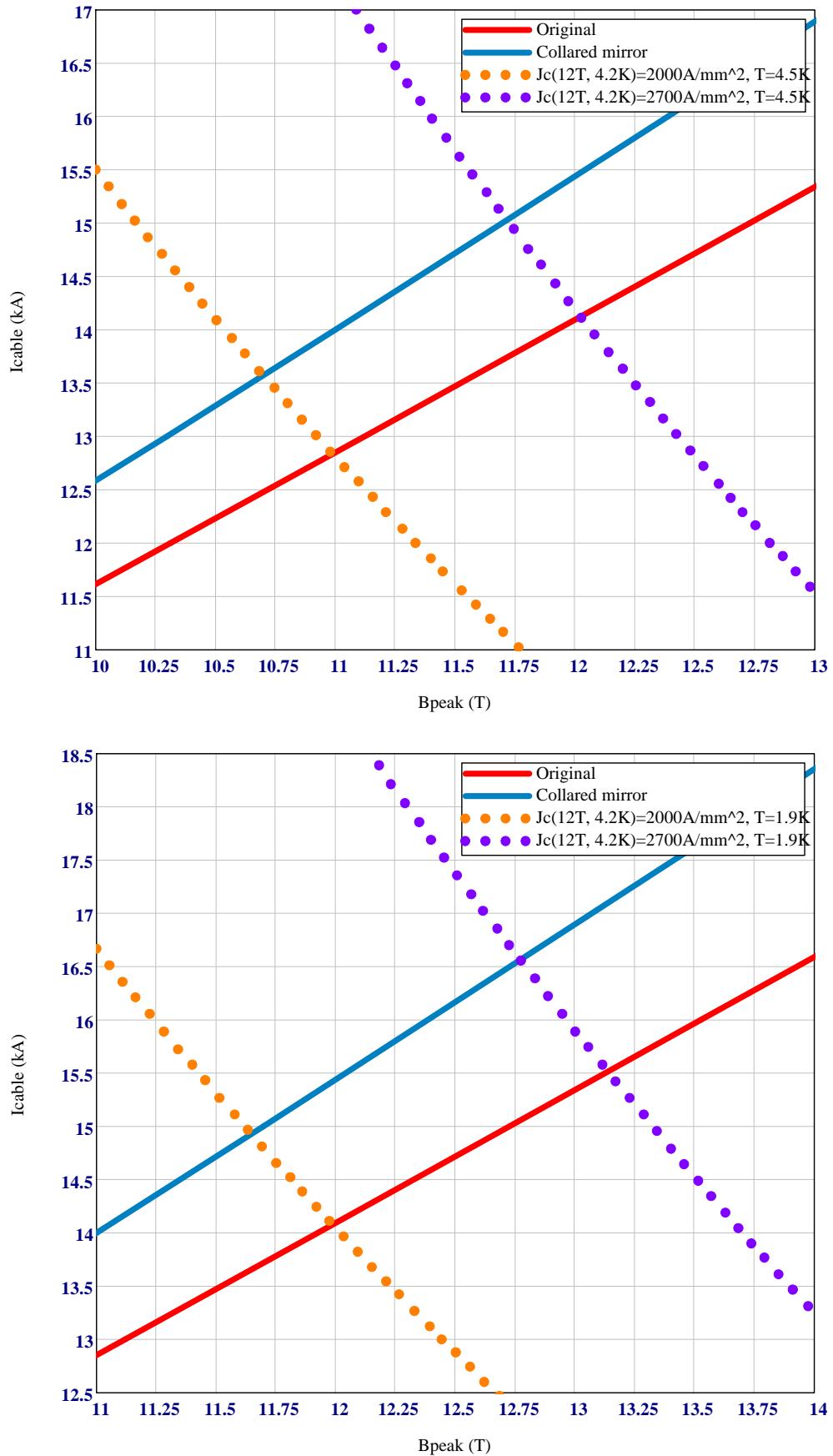


Figure 2. Load lines in the collared mirror design.

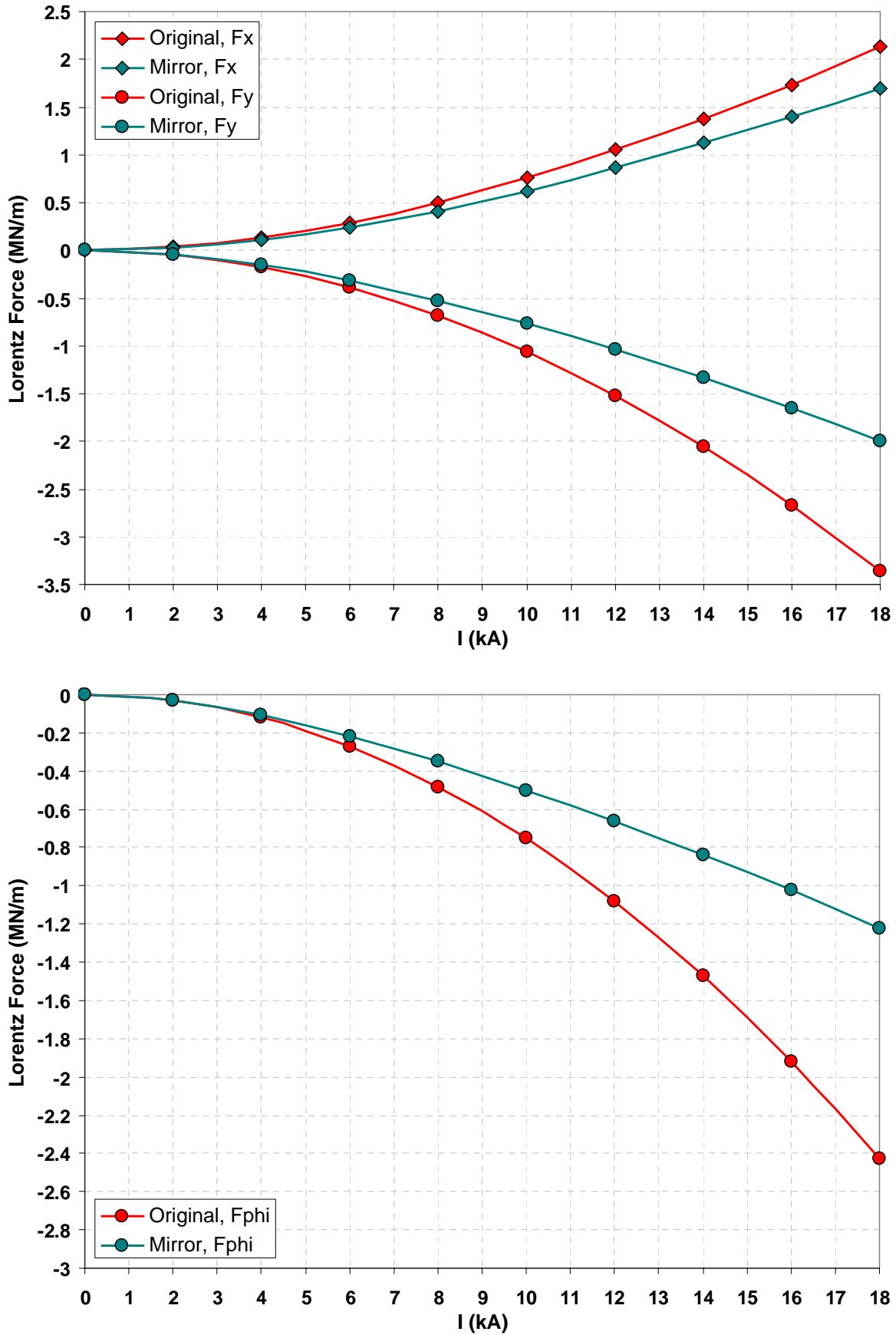


Figure 3. Lorentz forces per one coil octant in the collared mirror design.

Full Mirror Design with Stainless Steel Spacer

In order to increase the magnet transfer function and Lorentz forces, the magnetic mirror was extended all the way to the iron yoke. The collar structure is not appropriate in this case and the magnet has to be assembled and prestressed by other means. The spacer between the coil and iron yoke can be made of stainless steel or any other non-magnetic material.

Fig. 4 presents the cross-sections of the full mirror design with magnetic field distribution and Fig. 5-6 show the load lines and Lorentz forces. The transfer function went up with respect to the previous case because of the mirror extension. However, the quench current for the high-J_c superconductor is still well above 15 kA at 1.9 K. The Lorentz forces are also up with the vertical force reaching ~70 % and the azimuthal force reaching ~63 % of the original values.

Full Mirror Design with Iron Spacer

The next step in analyzing the mirror model was to replace the stainless steel spacer between coil and yoke with iron spacer as shown in Fig. 7. This further increased the transfer function such that the load line, presented in Fig. 8 intersects with that of the original design at ~13.8 kA current. It might be the design of choice, but the Lorentz force distribution is apparently skewed, as shown in Fig. 9. The horizontal force went up to ~120 % of the original value, while the vertical force practically did not change and the azimuthal force is down to ~58 % of the original. Such force redistribution explains by the coil attraction to the iron spacer, which shifts a fraction of the azimuthal force to the radial force.

Full Mirror Design with Stainless Steel Spacer and Iron Insert

In spite of the lower transfer function, the design with the stainless steel spacer seems to be a better choice than the design with the iron spacer because of the right force distribution. Another attempt to increase the transfer function was made by placing the quarter-round iron insert into the bore of the design with stainless steel spacer.

Fig. 10 shows the magnet cross-section with magnetic field distribution. The radius of the round part of the insert was fixed at 40.5 mm that makes the transfer function (and peak field), presented in Fig. 11, identical to the original at 14 kA current. As opposed to the design with the iron spacer, the Lorentz force distribution shown in Fig. 12 is correct with the horizontal, vertical, and azimuthal forces reaching 80 %, 78 %, and 74 % respectively. These force fractions increase at lower currents with the vertical and azimuthal forces getting equal to the original values at 8 kA current.

Summary

Several quadrupole magnet designs with magnetic mirror have been analyzed. It was found that the collared mirror design does not provide the original level of Lorentz forces, making it necessary to depart from the collar structure to the full mirror.

The full mirror design with the stainless steel spacer has higher transfer function and Lorentz forces than the collared mirror design, although still far from the original values. An attempt to increase the transfer function and forces by using the iron spacer was unsuccessful because of improper force distribution in the coil.

It was determined that the full mirror design with the stainless steel (or any other non-magnetic) spacer and quarter-round iron bore insert is the best TQ mirror design that matches the original transfer function and retains 74-80 % of the original Lorentz forces at 14 kA current.

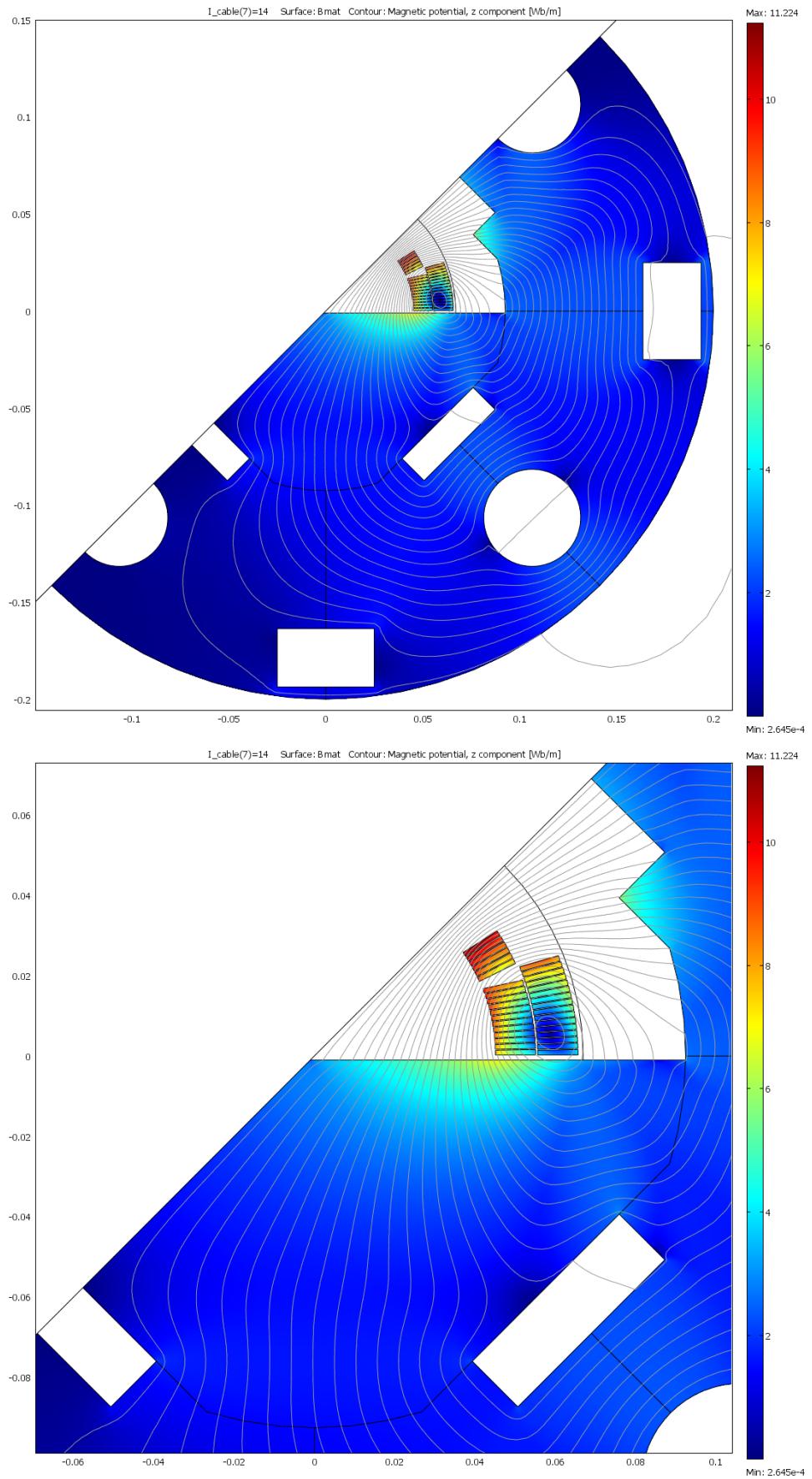


Figure 4. Magnetic field in the full mirror design with SS spacer at 14 kA.

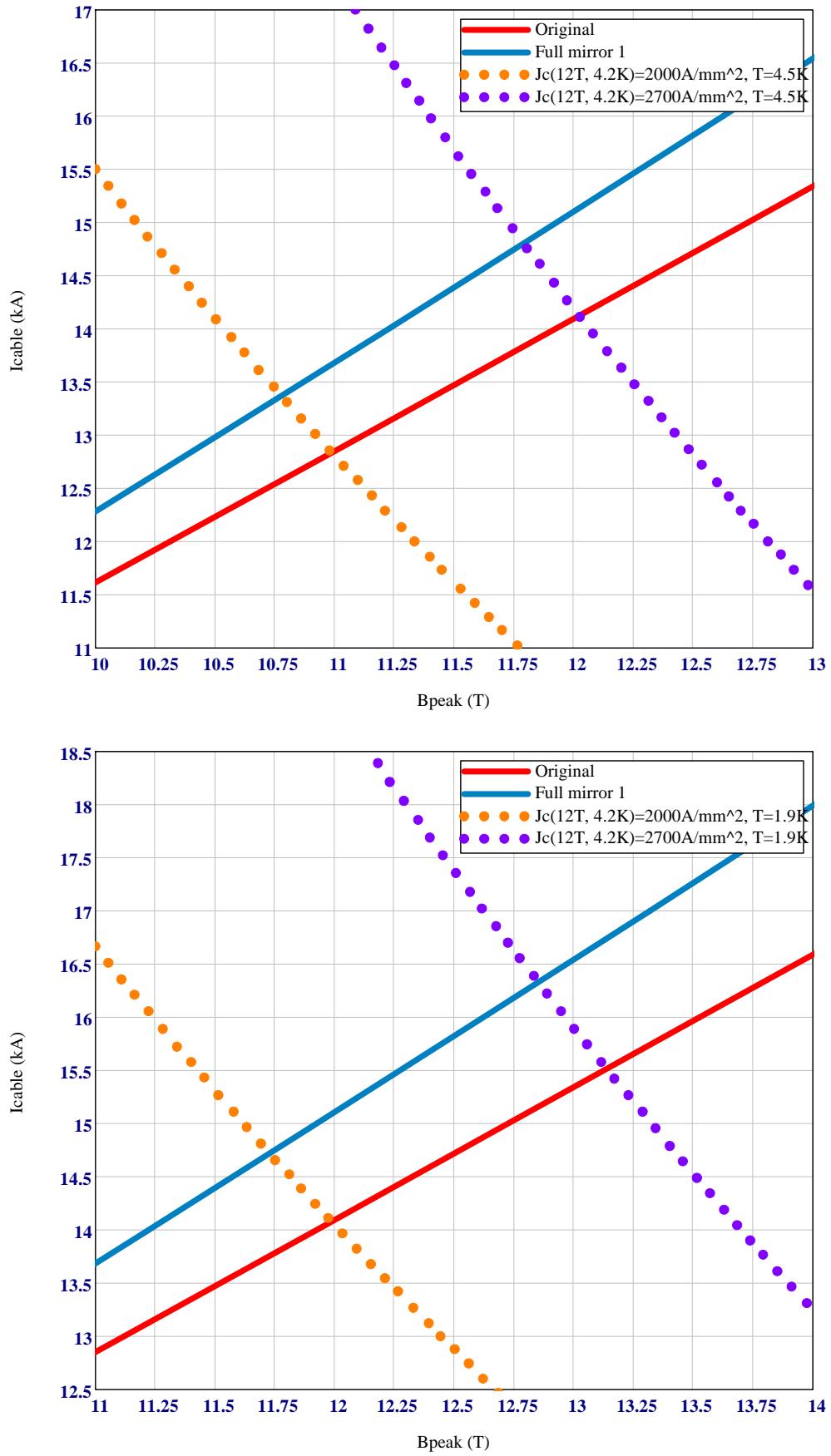


Figure 5. Load lines in the full mirror design with SS spacer.

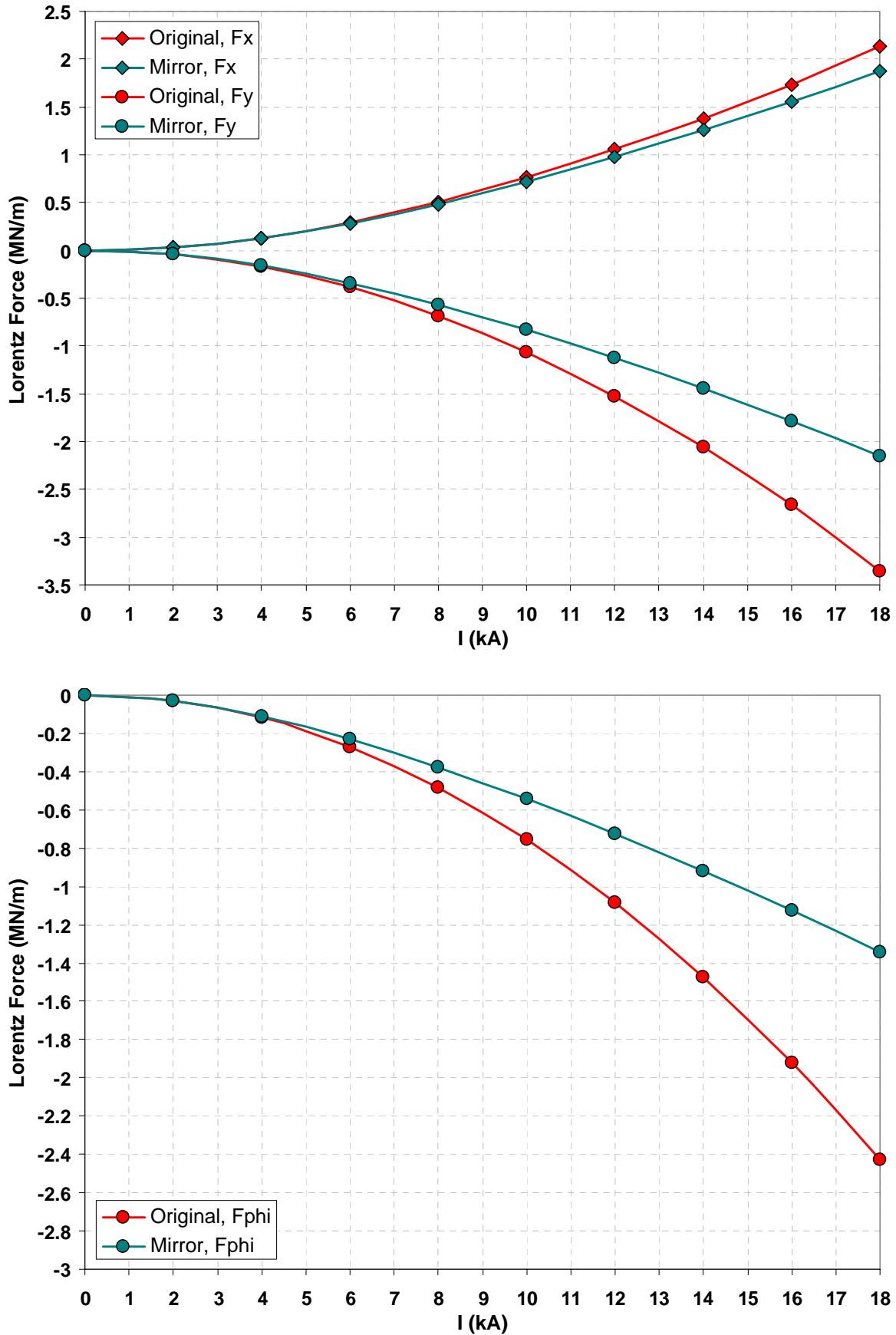


Figure 6. Lorentz forces in the full mirror design with SS spacer.

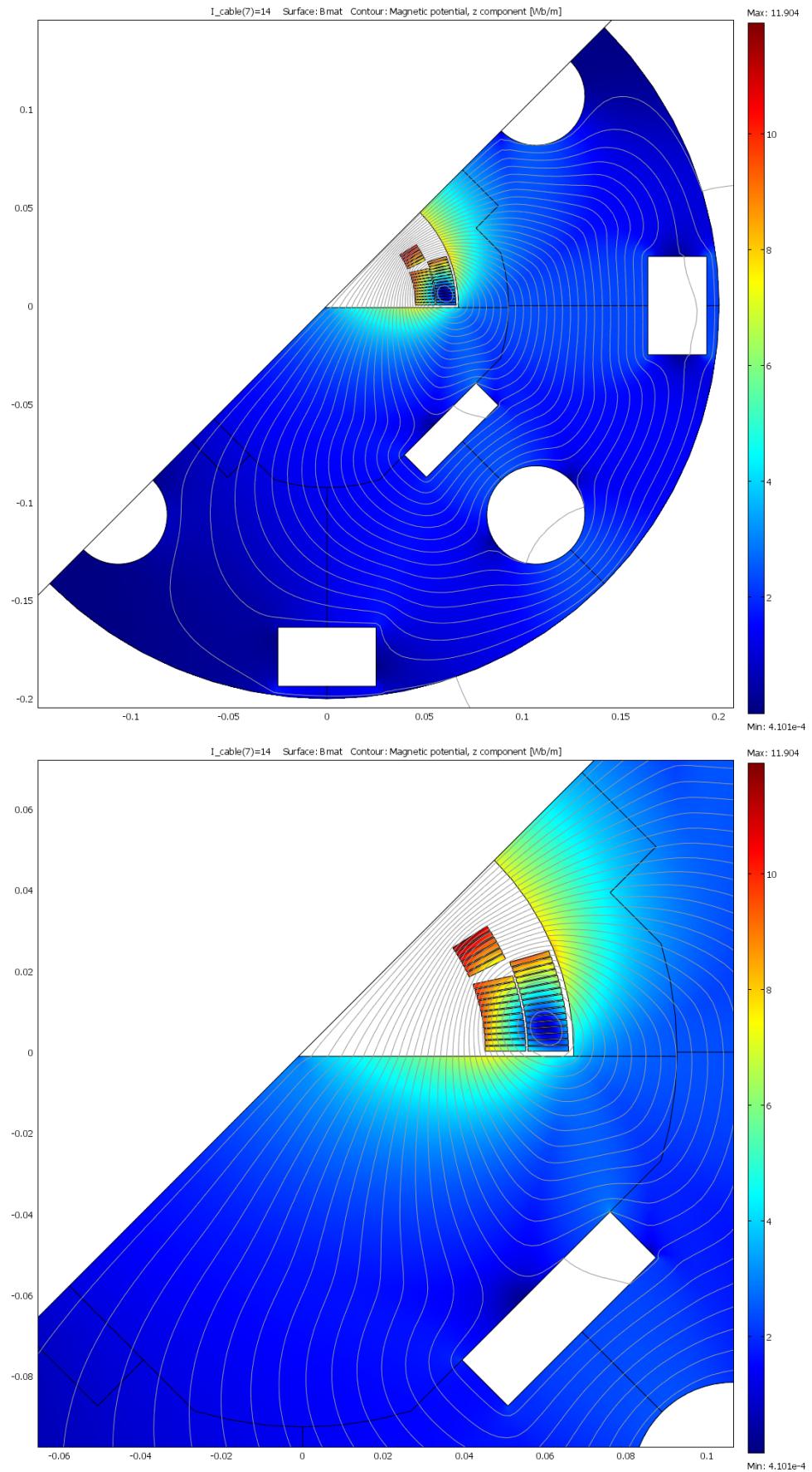


Figure 7. Magnetic field in the full mirror design with iron spacer at 14 kA.

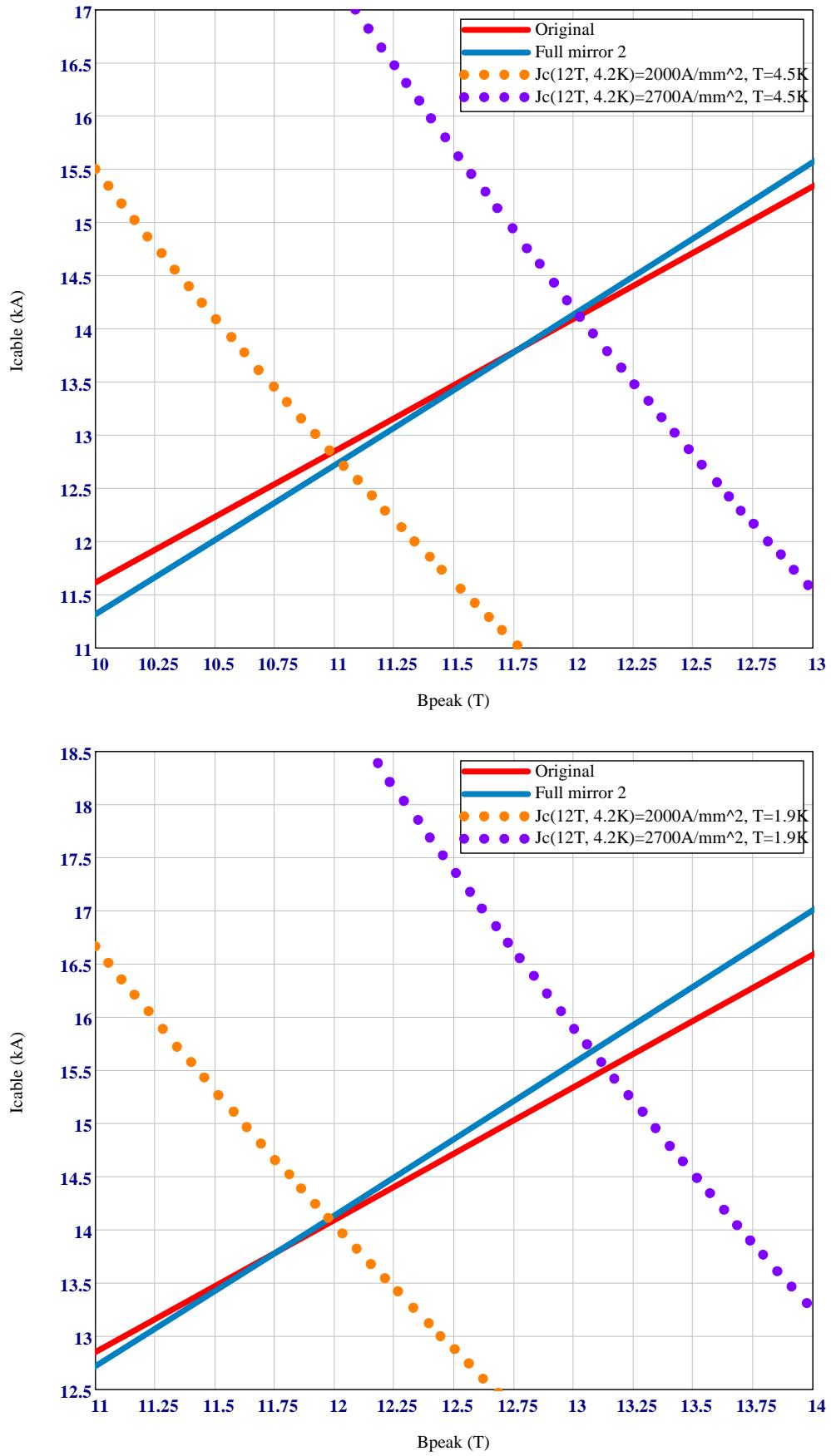


Figure 8. Load lines in the full mirror design with iron spacer.

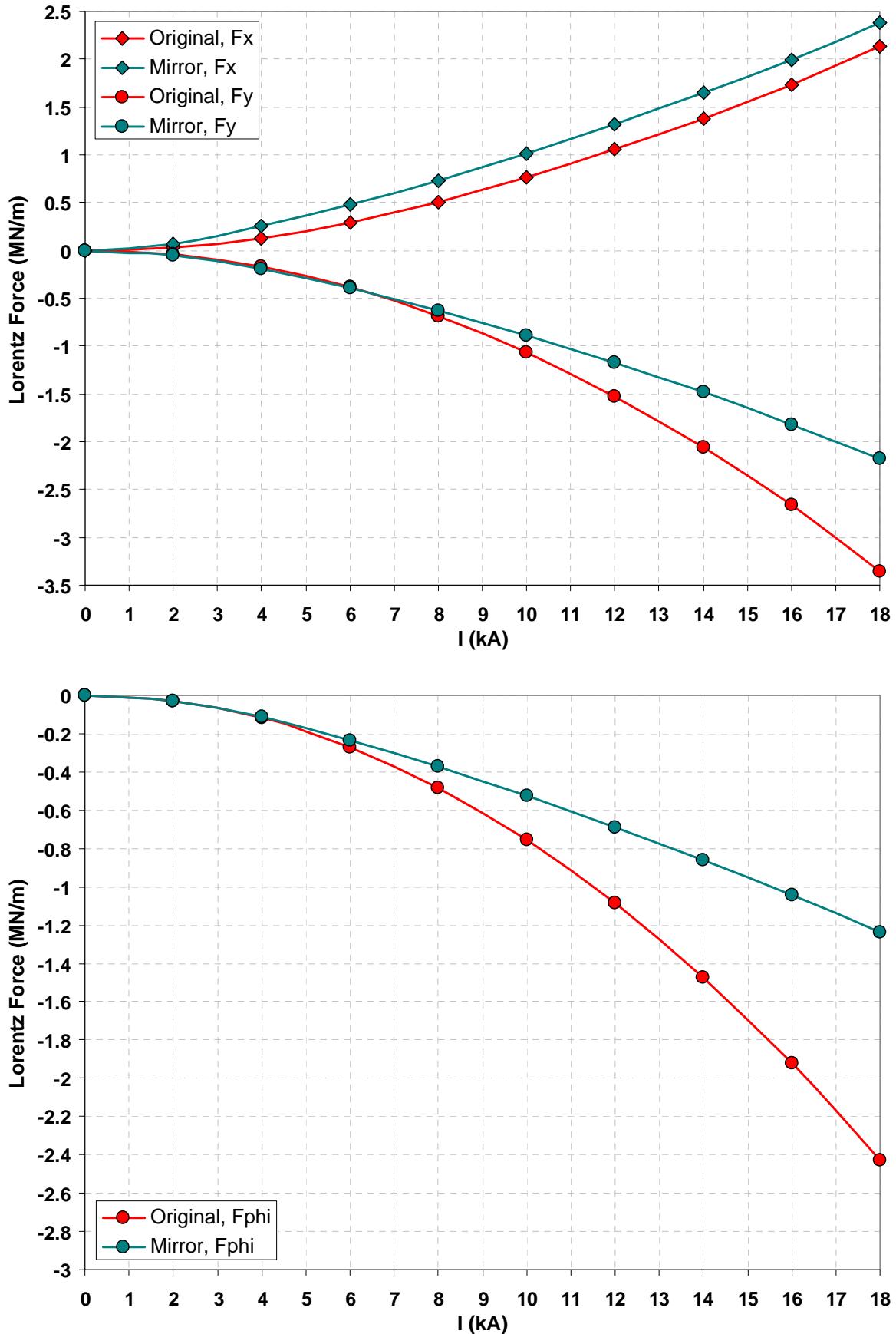


Figure 9. Lorentz forces in the full mirror design with iron spacer.

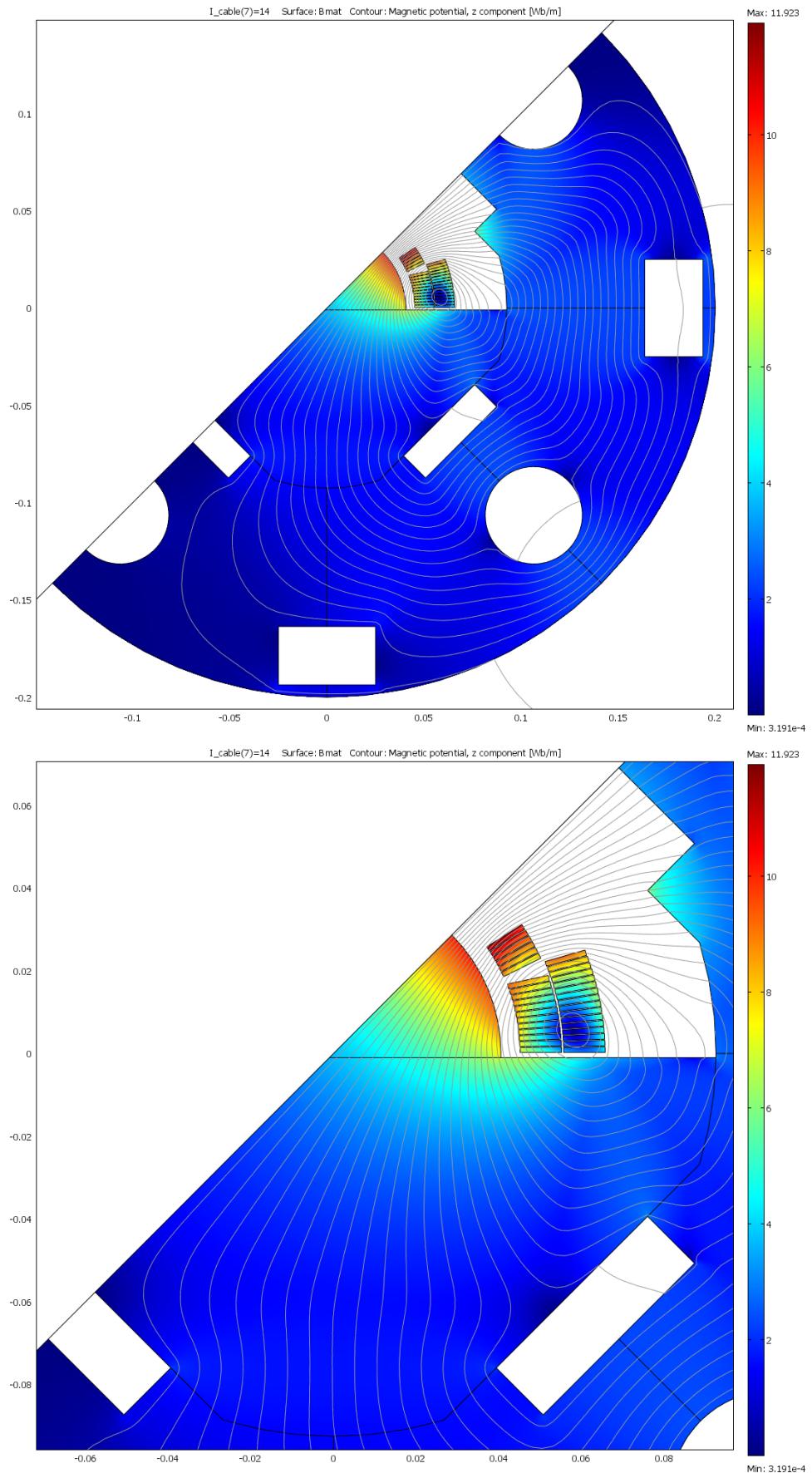


Figure 10. Magnetic field in the full mirror design with SS spacer and iron insert at 14 kA.

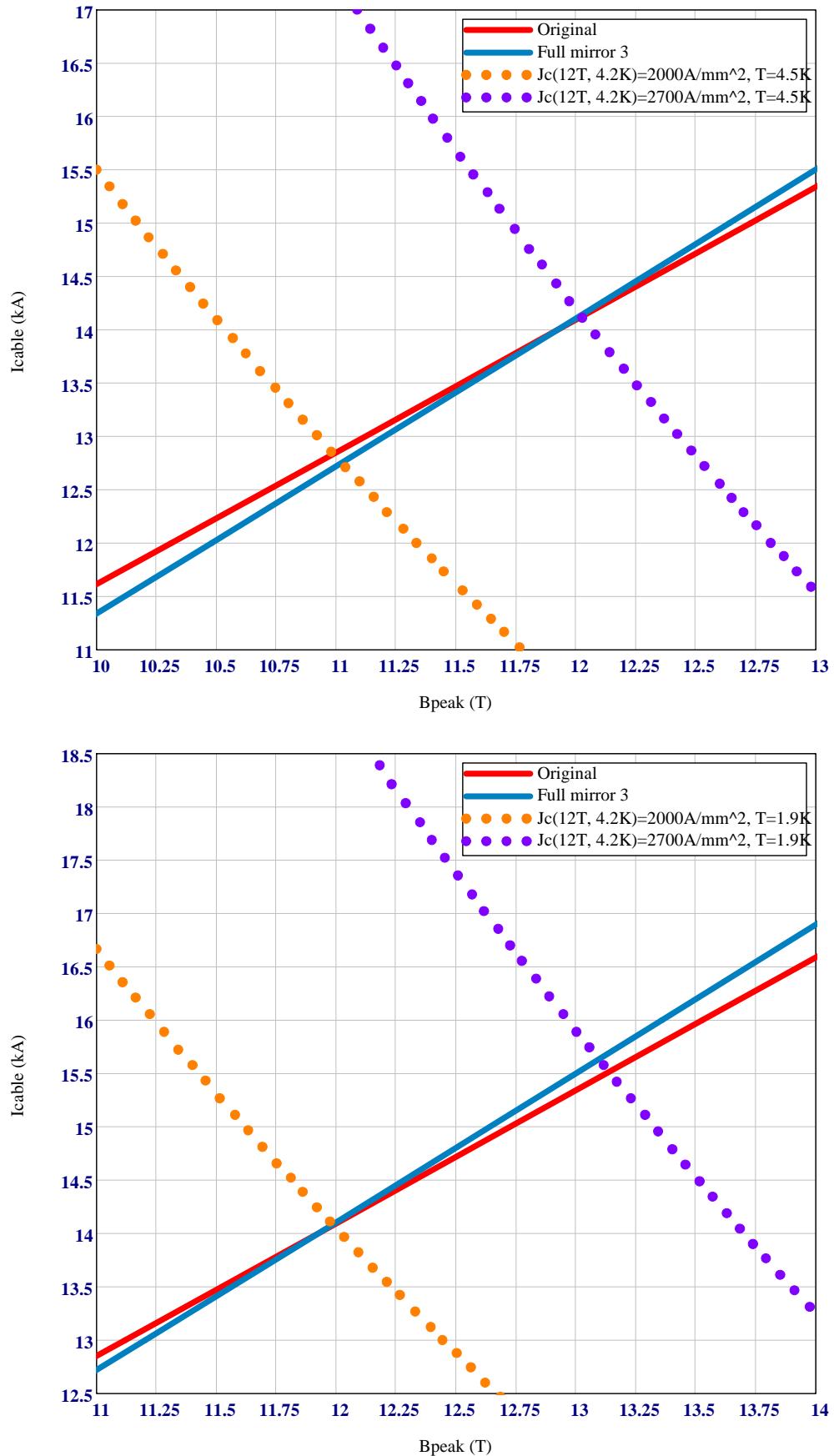


Figure 11. Load lines in the full mirror design with SS spacer and iron insert.

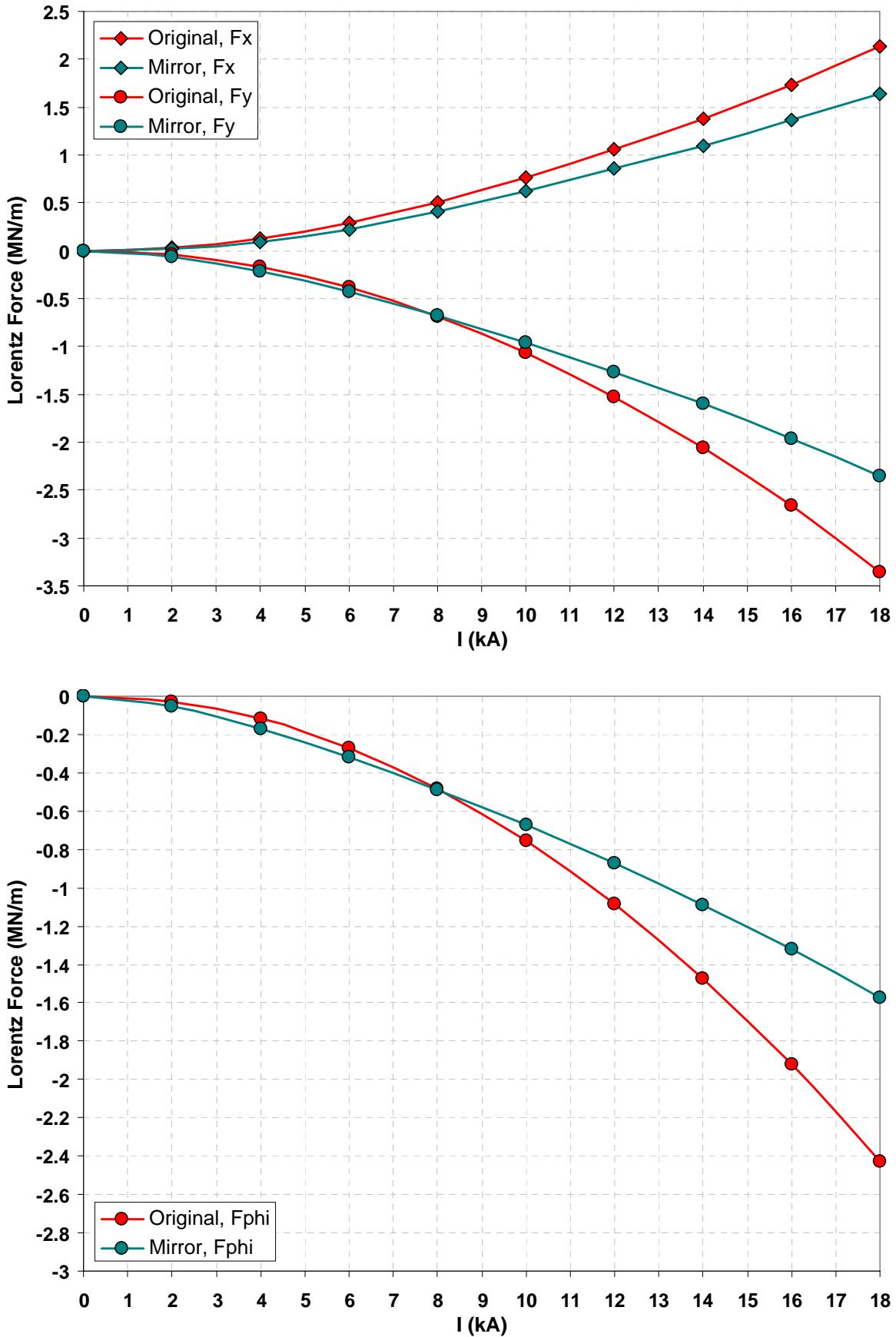


Figure 12. Lorentz forces in the full mirror design with SS spacer and iron insert.

References:

1. V.V. Kashikhin, A.V. Zlobin, "Magnetic Design of Mirror Magnets Based on Fermilab's Nb₃Sn Cos-theta Coils", *Fermilab Technical Note TD-02-045*, 02/12/02.
2. D. R. Chichili et al., "Design, fabrication and testing of Nb₃Sn shell type coils in mirror magnet configuration," *Adv. Cryogen. Eng.*, vol. 49A, pp. 775–782, 2004.
3. V.V. Kashikhin, A.V. Zlobin, "LARP Technology Quadrupole TQC01: 2D Magnetic Design and Analysis", *Fermilab Technical Note TD-05-052*, 12/13/05.